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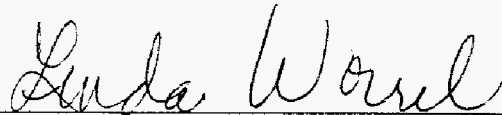   Optical Attenuation Calibrations of Surface Weather Observations

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Atmospheric Attenuation Calibrations of Surface Weather Observations

Babak Sanii, Jet Propulsion Lab, 3/12/01

Abstract

A correlation between near-IR atmospheric attenuation measurements made by the Atmospheric Visibility Monitor (AVM) at the Table Mountain Facility and airport surface weather observations at Edwards Air Force Base has been performed. High correlations (over 0.93) exist between the simultaneous Edwards observed sky cover and the average AVM measured attenuations over the course of the 10 months analyzed. The statistical relationship between the data-sets allows the determination of coarse attenuation statistics from the surface observations, suggesting that such statistics may be extrapolated from any surface weather observation site. Furthermore, a superior technique for converting AVM images to attenuation values by way of MODTRAN predictions has been demonstrated.

Introduction

A statistical description of optical atmospheric attenuation is one of the goals of the optical communication group at the Jet Propulsion Lab, particularly at specific laser spectral bands. Until now, statistics have been determined using the data collected by three Atmospheric Visibility Monitors (AVM). Recently, reports on the possible use of Surface Weather Observations[i] for attenuation modeling have prompted using AVM data to calibrate the qualitative surface weather observations to quantitative attenuation statistics. Because the surface weather observation sites are numerous and distributed over most of the US (they are frequently at most airports), the possibility of a statistical description of the atmospheric attenuation over the entire nation is enticing. This report describes the correlation between a single AVM and a single surface observation station. Further analysis corroborating these results using a second AVM are currently being pursued.

The Atmospheric Visibility Monitoring Program

The AVM program consists of three autonomous observatories connected to the Jet Propulsion Lab (JPL) by network. Each of the three observatories (figure 1) is stationed in the southwestern United States; they are located at Mt. Lemmon (near Tucson, AZ), the Table Mountain Facility (near Wrightwood, CA), and Goldstone Deep Space Communications Complex (near Barstow, CA). The three sites have been upgraded[ii] and are now gathering data using new processors, software, and cameras with greater near-infrared sensitivity and dynamic range. The sites are also networked to an atomic clock gateway, ensuring that they are on the same schedule and permitting accurate site-diversity statistics to be tabulated.
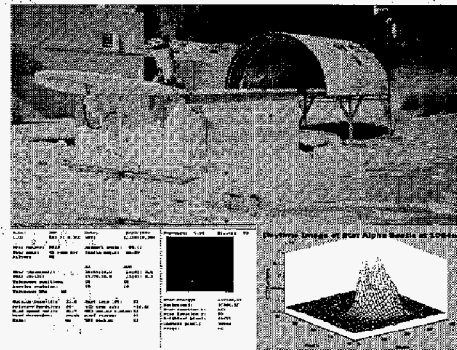

Figure 1. The Table Mountain Atmospheric Visibility Monitor (top), a screen-shot of the custom program (bottom left), and a sample of an acquired star image (bottom right).

Using motorized autonomous telescopes, the observatories take photometric readings of a set of bright stars through six optical filters. Three of these filters pass a narrow bandwidth of light which corresponds to laser wavelengths that may be used in future free-space optical communications systems, including 532nm (a frequency doubled Nd:YAG laser), 1064nm (the fundamental Nd:YAG wavelength), and 860nm (a common diode laser). Measurements at the increasingly popular 1550nm band are currently not supported by AVM. In addition to these, there are three other broadband astronomical filters in place: the Visual, Infrared and Blue filters. The observatory is completely automated, with environmental controls and alarms, and is capable of both day and night observing.

Post-processing enables the determination of a zenith-normalized attenuation value for every measurement. This process is described in greater detail below, where the new calibration technique is discussed. The new calibration technique employs the software tool of MODTRAN, which is an accepted standard for determining the spectral absorption and scattering of the atmosphere[iii].

Surface Weather Observations

The surface weather observations at Edwards Airforce Based used in this study are from the records gathered by the National Climatic Data Center (NCDC) from sites across the Unites States, and are readily available for purchase at nominal fees. Certified observers, using standards described in the Federal Meteorological Handbook (FMH), record hourly observations. Most of the surface weather observation sites are at airports.

Each observation consists of 23 fields, of which only the station, date, time, visibility and sky-cover are used in this report. Sky-cover is a defined by the FMH as "The amount of the celestial dome hidden by clouds and/or obscurations," and is expressed in four categories which are defined by how many eighths of the sky are obscured.

The four categories used at Edwards are:
Clear – No obscurations
Scattered – Any to 4/8 of the sky covered
Broken – 5/8 to 7/8 of the sky covered
Overcast – Complete coverage of the celestial dome

It should be noted that the FMH describes a fifth category, "Few" which was not implemented at Edwards for the dates of analysis. Edwards is approximately 65km from Table Mountain, and about 1000m lower in elevation, though line of sight exists between the two.

Analysis

The AVM Calibration Technique

The AVM measurements can be converted into transmission values by several methods. By comparing measurements taken at different elevation angles (corresponding to different line-of-sight air-masses), a value may be extrapolated that corresponds to a measurement above the atmosphere. Previously an exponential attenuation model of the atmosphere was used, producing a calibration value as shown in figure 2. By extrapolating back out to zero air-mass, the projected intensity above the atmosphere is determined. The slope of the line corresponds to the transmission at zenith (one air-mass), and this plot shows a transmission of %91, which is about 10% greater than MODTRAN predictions, and thus is of low confidence.
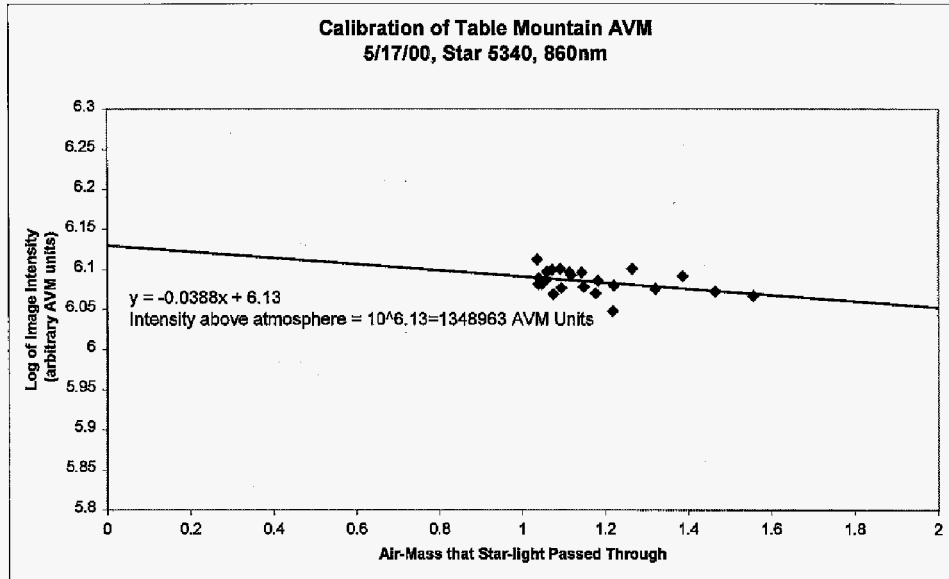
Figure 2. A calibration plot, where the log of intensities of the day's images are plotted against the air-mass traversed as the star's apparent position moves across the sky.

The exponential model is producing attenuations that are unphysical, and thus it is proving to be inadequate. Because the points in figure 2 are relatively co-linear, it is suspected that the exponential model's shortcomings are toward the lesser air-masses, where AVM has less data. Consequently, while a new model is being developed, MODTRAN predictions are being used to determine the calibration constant.

This is done by solving equation (1) for the calibration value I_o.

$$(1) \qquad Attenuation(dB) = -10 \log\left(\frac{Energy}{Exposure * I_o}\right)^{1/airmass}$$

Equation 1. Where Energy is the measured energy of the star in pixel values, exposure is its shutter-open-time in seconds, airmass is the mass of air that the star's light traversed (1 is normalized to zenith) and Io is the calibration constant that corresponds to the energy/exposure ratio that AVM would have measured if it were above the atmosphere.

The attenuation is set to the MODTRAN prediction for the altitude and wavelength of the measurement, the air-mass is derived from the elevation of the star at the time of the measurement and the energy represents the measurement itself. By performing this conversion on a set of measurements for one star, through one filter, a significant range of possible calibration values are produced for each day. Selecting the best one is a non-trivial task; on one hand one would want to select the greatest measurement in the entire set, because this is likely to be an image taken when the atmospheric condition is photometric and thus most closely matches the MODTRAN prediction. On the other hand, one must account for time degradation of the AVM system's optical transmission due to dust gathering on the exposed optical surfaces. This means that a single calibration value will not suffice and a time varying calibration value set is necessary. Experience showed that using the greatest calibration value for a rolling two week window produced a high likelihood of catching at least one clear-atmosphere image, and at the same time tracked the gradual optical degradation of the AVM system. By calibrating to MODTRAN, the calibration constants are more consistent and centered about a more realistic value than by way of the exponential model.
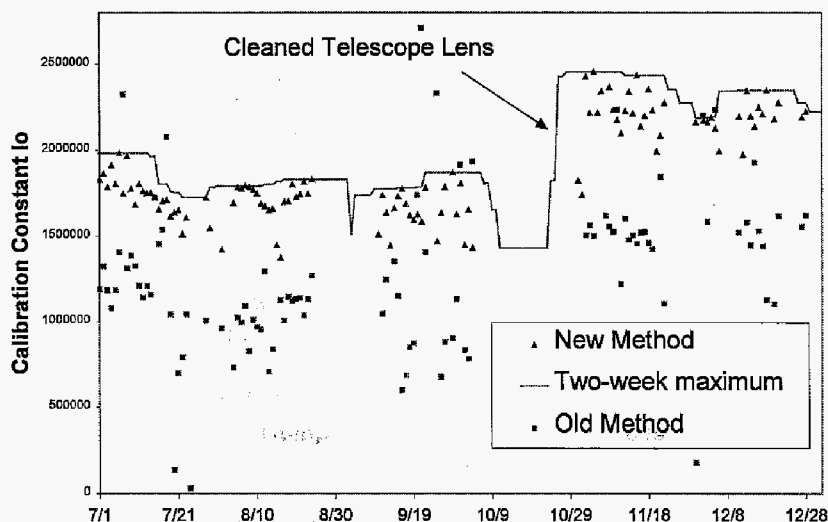
Comparing Calibration Techniques

Figure 3. Daily calibration values using the old method, the new method and the two-week maximum of the new method are shown. On Nov. 1st the telescope's Schmidt corrector was cleaned, and the expected calibration increase was experienced. The two-week maximum is used in all further analysis. This data represents images of Alpha-Boo taken through an 860nm filter.

Using this set of calibration values, attenuation was determined for observations throughout the year 2000. Figure 4 presents these values as a cumulative distribution function (CDF). This format is useful for optical communication mission designers, who need to know what percentage of the time they can expect to have a given (or better) transmission through the atmosphere. Further work can be done refining the MODTRAN model for better calibration, perhaps by way of FASCOD3 seasonal atmospheric compensations.
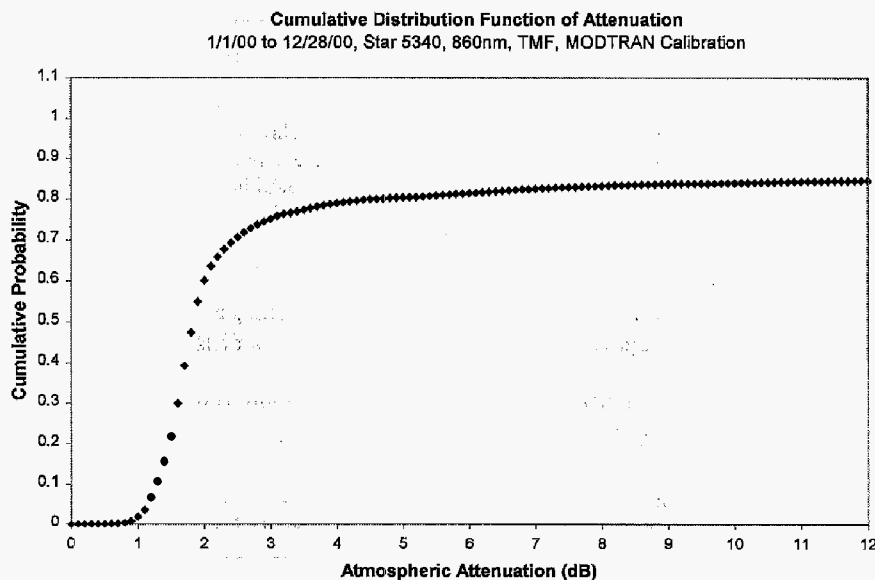

Figure 4. A cumulative distribution function for the attenuation observed at Table Mountain through an 860nm narrowband filter. This data uses the new MODTRAN calibration method.

Surface Weather Observation Correlation

Because the surface weather data and the AVM data are both time-tagged, it is possible to merge the data-sets by way of Microsoft Access. Once merged, a statistical correlation of various subsets is possible, yielding a relationship between the two. This relationship can be used to supplement AVM data for when system outages occur, as well as synthesize results from the larger database that extends to before the AVM program began. Furthermore, this allows the possibility of synthesizing attenuation statistics at other observation sites around the country, and correcting for altitude differences by way of MODTRAN predictions.

Most of the analysis concentrates on the relationship between AVM attenuation measurements and the surface observed cloud-cover. Other surface observations, such as visibility and cloud-height, were also investigated, but with much less interesting results. The correlation values between the average attenuation and the visibility and cloud height are 0.62 and 0.46 respectively (with 10 and 15 degrees of freedom respectively). Good correlations were not expected because AVM measures attenuation along a vertical path, and these observations have ramifications largely in horizontal attenuation.

The process began by binning the AVM measured attenuations into groups based on the surface observed cloud cover at the time of the measurement. For each cloud cover category, a distribution of measured attenuations was determined; results are presented in figure 5. The distributions spread significantly as one experiences more severe cloud-cover, and the mean attenuation for each cloud-cover bin increases.
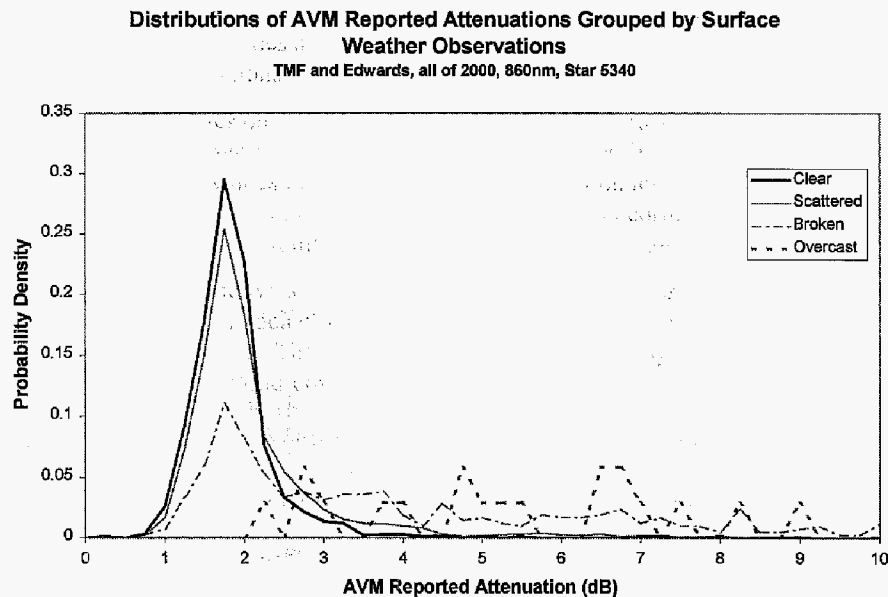
Distributions of AVM Reported Attenuations Grouped by Surface Weather Observations
TMF and Edwards, all of 2000, 860nm, Star 5340

Figure 5. The distributions of measured attenuations seen at Table Mountain when Edwards reported a given sky-cover category.

The AVM system has a fundamental threshold: if it cannot see the star, it cannot determine the precise attenuation. Generally this sensitivity threshold is about 10dB attenuation at 860nm, but varies with wavelength, star intensity and current sky background. When this occurs, the star is considered "blocked" for communication purposes, and the measurement is assigned an arbitrarily high number of 30dB. To correctly correlate AVM and Surface Weather data, two sets of statistics are tracked: the average attenuation when AVM could "see" the star, and the percentage of the time when AVM could not "see" the star. These statistics are binned according to the sky cover observed simultaneously at Edwards, and are presented in figure 6.

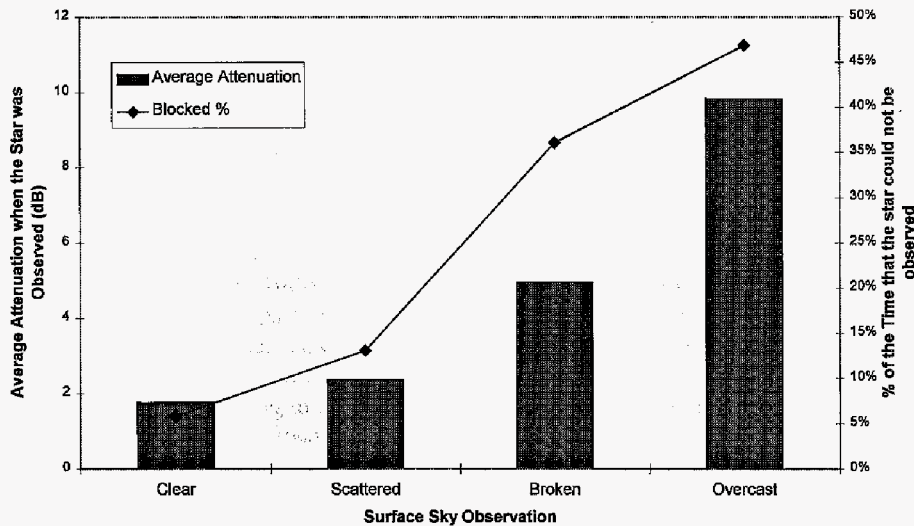**Average Attenuation Statistics for Surface Sky Observation Catagories**

Figure 6. For each sky category, the corresponding AVM data-set was analyzed. Shown are the average attenuations and the percentage of "blocked" images (i.e. beyond the sensitivity of the AVM, thus very attenuated).

By converting the sky-cover categories to their average % of cloud-cover (using the definitions presented in the introduction), a correlation between the statistics of figure 6 and the cloud cover may be performed. This yields correlation coefficients of 0.930 between the sky cover and the average simultaneously reported attenuation, and 0.998, between the sky cover and the % of time-blocked. Both values have two-degrees of freedom.

One may be concerned that the % of time blocked neither begins at 0 (when it is presumably clear) nor ends at 100% (when it is presumably completely overcast). The explanation seems to lie in the greater sensitivity of the AVM system to that of the human eye. The camera is configured to allow exposures of up to 15 seconds (compared to about 1/10 s in the human eye), and its telescope's aperture is 10 inches (approximately 30 times that of the eye). This is corroborated by the time of day when these "erroneous" observations take place. The majority of these observations occur around twilight, when the human eye's response is worse, and while AVM can still perform its long exposures (because the sky isn't very bright yet). The dis-correlation is apparently not a function of the distance between Edwards and Table Mountain. The argument for this is built by isolating the "erroneous" points (unblocked measurements when it was overcast, or blocked measurement when it was clear) and plotting the azimuth of the AVM measurement at that time. If distance were the issue, one would expect a cluster of "erroneous" measurements on the West, opposite the direction to Edwards. In fact there was no discernable pattern in these points.

With the added confidence of these high correlation values, the next task was to invert the analysis and use the surface weather observations to statistically predict the attenuation. This process consists largely of bookkeeping; for whatever number of a sky-cover category observations one has, one multiplies it by the determined "% of time blocked" and records that as a 30dB attenuation (the arbitrarily high one). The remaining observations are given an attenuation equal to the average unblocked attenuation. This process is repeated for each surface weather category, and can be seen in table 1, with the cumulative distribution function of attenuation presented in table 2 (using the time period when the TMF AVM was operational between 1/1/00 and 11/17/00).

Sky Category	# of observations	% of measurements blocked	# at 30dB	Average attenuation	# at average attenuation
Clear	1865	5.791%	108.002	1.75658	1756.998
Scattered	2570	13.074%	336.002	2.354053	2233.998
Broken	650	36.000%	234	4.936654	416
Overcast	64	46.875%	30	9.827009	34
Sky Category	'X'	Known Percentage 'B'	X*B	Known Average 'A'	(1-B)*X*A

Table 1. An example of how the book-keeping for determining the attenuation statistics are kept.

Attenuation	Number of Counts	Probability Density	Cumulative Distribution
1.75658	1757	0.341231	0.341231
2.354053	2234	0.433871	0.775102
4.936654	416	0.080792	0.855894
9.827009	34	0.006603	0.862498
30	708	0.137502	1

Table 2. The Generated Cumulative Distribution Function

As a sanity check, this cumulative distribution function (CDF) was compared with the one determined from AVM data, shown in figure 7.

AVM Attenuation Measurements compared with Surface Observation Synthesized Results

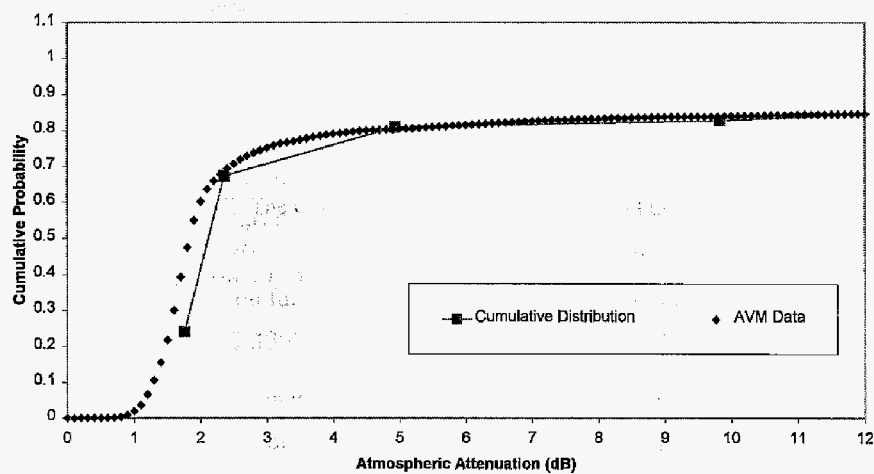1/1/00 to 12/28/00, Star 5340, 860nm, TMF, MODTRAN Calibration

Figure 7. The cumulative distribution function of figure 4, overlayed with the projected cumulative distribution function derived from the surface weather observations. While this is not a surprise, as one set of data was used to calibrate the other, it is certainly a good "check" for the process.

This process now enables two possible capabilities:

1) The capability to use other surface weather observation sites to generate local atmospheric attenuation statistics (correcting for local elevation by way of MODTRAN).

2) The ability to supplement the data-set for the AVM at Table Mountain, correcting for system outages.

The first is being pursued by comparing the Goldstone AVM and the nearby Barstow-Daggett airport observations, but to initial appearances more AVM observations from Goldstone will be needed before that study may be performed.

The second can be readily demonstrated by examining the Table Mountain AVM data-set, and isolating outages. This is a particularly important demonstration, because the system outages for the majority of the year 2000 were not random, but systematic. The rain-recovery software routines were fixed in November; prior to that every time it rained the system needed to be manually restarted, often hours to days later (particularly on the weekends). Consequently valid measurements of rain (which is interpreted as opaque attenuation) and the typically cloudy portion immediately after it stops raining are not included in the set. However, at Edwards the surface observations continued unhindered. Note that this does not affect our correlation statistics significantly because each measurement was compared to each observation directly and independently from the rest of the set. Figure 8 demonstrates the systematic bias of the previous year's AVM data using surface weather observations.
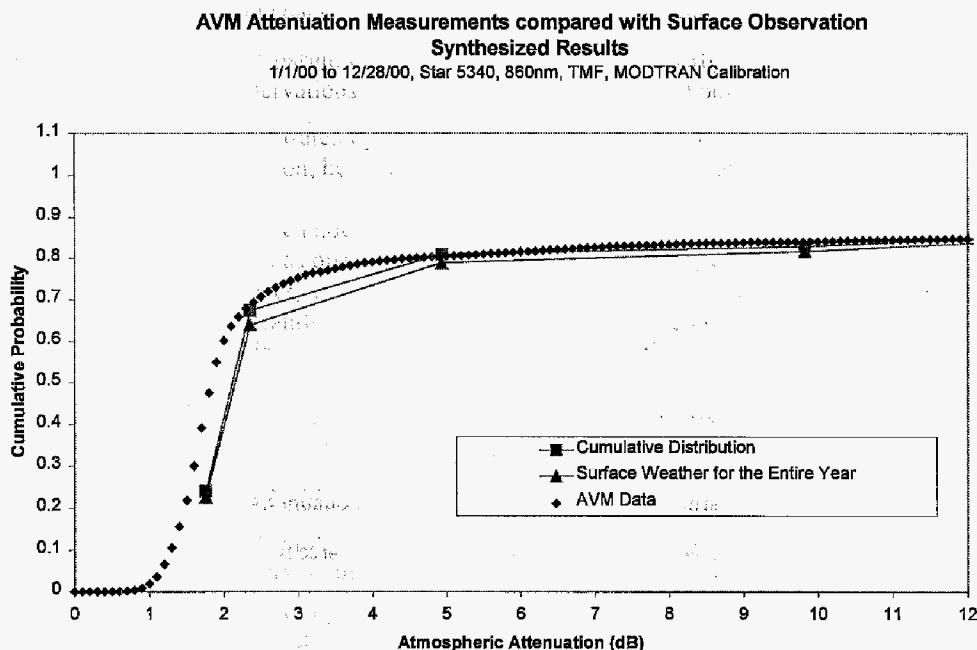
AVM Attenuation Measurements compared with Surface Observation Synthesized Results
1/1/00 to 12/28/00, Star 5340, 860nm, TMF, MODTRAN Calibration

Figure 8 has the projected surface-weather observation CDF derived from the sky-cover ratings of the entire year, as opposed to those of only when AVM was operational (such as figure 7, whose plots are overlayed here for reference).

Finally, a cumulative distribution function of the AVM data supplemented by the surface observation data is presented in figure 9. This was done by scaling the five CDF points (determined from the surface observation data) by the fraction of the time-range they represented. Then the AVM data was similarly scaled, and the two were summed together.
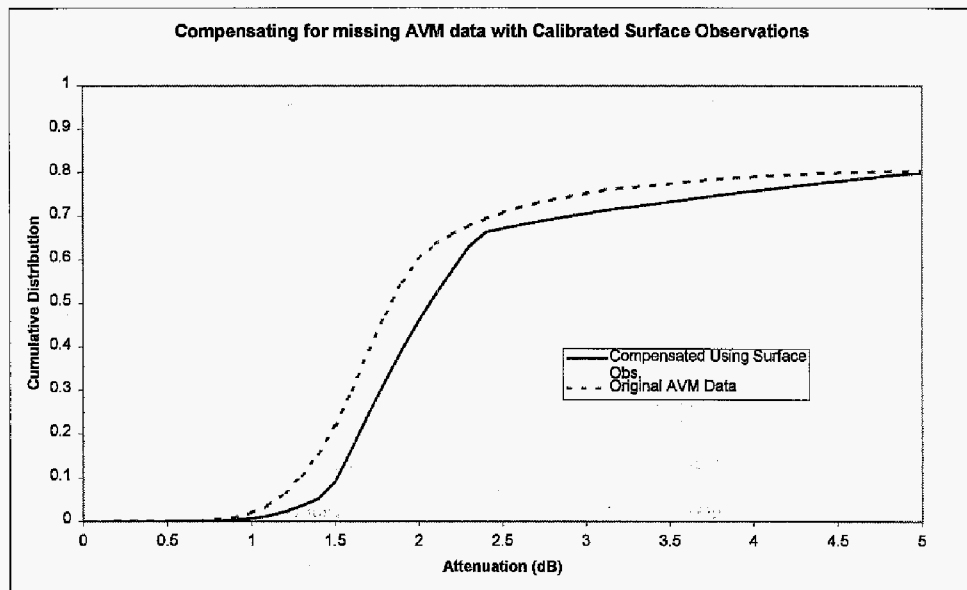
Compensating for missing AVM data with Calibrated Surface Observations

Figure 9 shows the combined cumulative distribution function of the AVM data and the calibrated surface observations for the period when there was no AVM data. The CDF of just the AVM data is also presented for reference. This data is from 1/1/00 to 11/11/00, at 860nm, from Table Mountain AVM and Edwards Surface Observations.

Conclusions

A strong correlation exists between the sky-cover surface weather observations performed at Edwards Air Force base in California, and the Atmospheric Visibility Monitor attenuations measured at the nearby Table Mountain between 1/1/00 and 11/11/00. The correlation co-efficient between the sky-cover observation and the average attenuation measurement is 0.930, and the co-efficient between the same and the percentage of time unblocked was 0.998 . Furthermore, a new calibration procedure based on MODTRAN predictions has been demonstrated, and proves to be effective.

Further work is being performed in corroborating this reported correlation with observations at the Barstow-Dagget airport and the AVM at Goldstone. If this proves successful, this may be an effective tool to determine the attenuation statistics near all surface observation sites following standards of the Federal Meteorological Handbook.

Acknowledgements

[i] S. Piazzolla, S. Slobin, P.E. Amini "Cloud Coverage Diversity Statistics for Optical Communication in the Southwestern United States" JPL Publication 00-13 2000.

[ii] B. Sanii, A. Datta, D. Tsiang, J. Wu and A. Biswas "Preliminary Results of an Upgraded Atmospheric Visibility Monitoring Station" *TMO Progress Report 42-142* 2000.

[iii] H.E. Snell, G.P. Anderson, J.Wang, J.-L. Moncet, J.H. Chetwynd, S.J. English, Validation of FASE (FASCODE for the Environment) and MODTRAN3: Updates and Comparisons with Clear-Sky Measurements, The European Symposium on Satellite Remote Sensing, Conference on Passive Infrared Remote Sensing of Clouds and the Atmosphere III, Proceedings of SPIE, Paris, France, 1995.

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